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UNSTEADY FLOW IN OPEN TYPE PIPE IRRIGATION SYSTEMS

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IRRIGATION AND DRAINAGE DIVISION

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UNSTEADY FLOW IN OPEN TYPE PIPE IRRIGATION SYSTEMS

E. H. Taylor, A.M. ASCE, A. F. Pillsbury, T. O. Ellis, and G. A. Bekey[1]

ABSTRACT

Severe "surging" has presented a serious operating difficulty in parts of the Coachella Valley (California) County Water District's irrigation distribution system. A model study of the mechanics of surge amplification is described and a mathematical analysis of the phenomenon is presented. Also a practical method of control of surging is offered by suggesting the use of properly placed vent pipes. The mathematical analysis is felt to be of interest because it was done mechanically. In this connection, the application of the University of California's differential analyzer to this problem is described. The agreement between the theoretical and the observed results is generally satisfactory although certain questions remain to be answered.

The Coachella Valley County Water District irrigation distribution system delivers water to each arable 40-acre tract through a low pressure open type pipe system. The static head is maintained at safely low levels by open stands in which overflow baffle walls are installed. The overflow stands are usually 1/4 mile apart, and the baffle walls serve the function of keeping the head between the elevations of the overflow crest and the top of the stand. A portion of a typical profile is indicated schematically in figure 1.

When certain long, relatively flat, laterals were placed in operation in 1950 severe "surging" was observed. In many cases the periodic rise and fall of the water surfaces in the stands were so severe that satisfactory deliveries could not be made. For half a minute or so there would be a big flush of water, commonly overflowing stands; then for another half minute or so there might be none.

J. H. Snyder, then Chief Engineer and General Manager of the District requested assistance, and the two senior authors spent some time in field studies of the system. Curtis (1)[2], Pillsbury (2) (3), and Taylor and Pillsbury (4) (5) have previously reported on this problem. The purpose of the present paper is to describe a later and more thorough series of model experiments in which the elevations of five fluctuating water surfaces were measured simultaneously, together with time. A mathematical analysis is presented, and the results are compared with experimental observations. This analysis is believed to be of particular interest since it was carried out by use of a mechanical differential analyzer.

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1. Respectively: Assoc. Prof. of Engineering, Prof. of Irrigation, Engr. Ass't. (responsible for setting problem up in differential analyzer and running same), and Jr. Engr. (in charge of differential analyzer)
2. Refers to literature cited.

Experimental Work

A model of a portion of a typical lateral was constructed to 1:12 scale. No effort was made to simulate any particular lateral, but simply to retain all essential hydraulic elements. A schematic diagram of the model is given in figure 2, and a picture of the stands in figure 3. Actually, the imaginary prototype would consist of 5 ft. diameter overflow stands spaced 1/4 mile apart on a 24 inch I.D. pipe line. The model stands are 5 inches I.D. plastic with 1/4 inch thick plastic baffles extending to a height of 21-3/4 inches above the centerline of the pipe (height of stands not necessarily to model scale.) The 110 ft. reach of pipe between each stand is 2 inch I.D. The first 9 feet of pipe below each stand is clear plastic, and the balance of each line is standard 2 inch galvanized pipe. There is a difference in elevation between each of four stands of approximately 1.4 feet, and the three reaches of pipe are approximately on a slope of 0.013. The reaches of pipe were looped back upon one-another, as shown in figure 2, to a.) conserve space, and to b.) locate all four stands together.

Notation will be as established in figure 4, in which the reaches appear as in a straight line.

Preliminary Tests

Time was spent on qualitative observations during the early phases of this study with the model. This permitted decisions to be reached as to the features of the problem most in need of analytical solution, and permitted instrumentation to be orderly planned.

It was found that when the flow in the system is sufficient to allow the overfalling water to spring clear of the baffle crests, air is drawn into the pool in the downstream side of the stand. This air forms a bubble immediately below the stand, as indicated in figures 5 and 6. With high flows, the bubble may grow to considerable size (it will go beyond the 9 ft. plastic section of pipe in the model), and air may sometimes be pumped clear through the reach. In all cases the bubble forms at the zone of separation and continues downstream to some point where it ends in an hydraulic jump.

Surge in the model is primarily initiated at moderately small flows wherein the bubble forms, grows a little, and then blows back up the stand. As it forms and grows, water is displaced. This results in a rise in the pool level, and an acceleration of the flow in the pipe. As the acceleration continues, there is a greater rate of discharge than there is water flowing into the pool. Consequently, the pool level starts to fall slightly. Now, the pressure within the bubble is related to the pool level, and when this level is lowered even a small amount, the air begins to escape back up through the pool. The storage space thus created receives water from the pool, the pool level drops further, bubble pressure is further relieved, all with the result that the bubble disappears very rapidly once the "blow-back" process is initiated. The pool level now has fallen to an elevation less than that necessary to maintain steady flow. With deceleration of flow, the pool level starts to rise, and the process of bubble formation and blow-back is repeated. Each stand in the system may be experiencing the same phenomenon, with the result that those downstream have a fluctuating component impressed upon them from above.

Now, it is essential to point out that the portion of a system comprised of, say, the downstream side of stand A, the upstream side of stand B, and the connecting pipe resembles a large U-tube, and has the oscillatory properties

of such a tube. If friction could be disregarded, the natural frequency of such a reach would be, in cycles per second,

$$f = \frac{1}{2\pi} \sqrt{\frac{a\,g}{A\,l}}$$

in which,

a = pipe cross section in sq. ft.
A = stand half area in sq. ft.
l = length of connecting pipe in feet.
g = gravitational force per unit mass in ft./sec.^{2}

Suppose now that stand A impresses a slightly fluctuating flow on B due to the bubble-making process just described. Reach 2, comprising the downstream side of B and the upstream side of C plus the connecting pipe, reacts to the unsteady inflow in much the same way as a harmonic system reacts to a random excitation. In other words, if the exciting influence contains components near the natural frequency of the reach, the reach will oscillate at its natural frequency. Thus, it may be expected that the flow over stand C will fluctuate more severely than that over B. Moreover, reach 2 will have "filtered" out most of the randomness of the excitation from reach 1. This results in the application to reach 3 of a rythmic pulse in resonance with the natural frequency of that reach. Reach 3, therefore, may be expected to be thrown into violent oscillation.

Preliminary observations substantiated the above qualitative analysis. For rates of inflow which would cause periodic bubble formation, it was noted that while the elevation z_2, in stand B would fluctuate only a few thousandths of an inch, changes of as much as 8 - 10 inches were observed in the elevation z_3 in stand D. The level would drop below the baffle crest of this stand, and during part of the oscillatory cycle the flow in the pipe would actually be in the reverse direction.

It has been suggested (1) that the surge amplification could be eliminated by arranging the natural frequencies of successive reaches in such a way as to avoid resonance. However, practical considerations involved in the layout of a system often make this difficult. Operational troubles with lids and gates which are used to accomplish the same purpose also render those practices undesirable. It appeared logical to the authors that complete removal of the exciting influence would bring about beneficial results. Accordingly, vents, consisting of 1-1/4 inch I.D. clear plastic tubes were installed below the stands, as shown in figure 7.

With vents of adequate size[3] that fraction of the entrained air which had previously gathered in a bubble was released at a uniform rate through the vent. Surging dampened out in a few minutes, and perfectly steady flows were maintained.

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3. Smaller vents were first tried which reduced, but did not entirely eliminate, surge. From observation it would appear that the size used was just barely adequate to completely eliminate excitation. To remove excitation, vents should be as close to the stand as practical. The vents used were not adequate in size nor correctly located to remove all air during steady high flows, thus maximum capacity was impaired. For this purpose it might be desirable to have the vents the full size of the pipe for at least some distance above the pipe (6) and to provide a supplemental vent some distance downstream.

It is interesting to note that, with stands B and C vented and with only stand A contributing to bubble formation, surge amplification was essentially as great as had been observed when B and C were making their own bubbles. It was possible to establish a perfectly steady flow with all stands vented, then plug the first vent and observe the growth of surge. Conversely, removal of the plug resulted in a gradual damping out of the oscillation. The possibility of changing instantly from a steady to an unsteady flow provided a simple technique by which the empirical characteristics of the model could be evaluated, and helped in the planning of a program of quantitative investigation.

Quantitative Tests

The problem of surge amplification was selected as that aspect of the phenomenon most interesting to study in detail. In this study attention was confined to reaches 2 and 3. The intent was to measure the temporal fluctuations in flow over stands B, C, and D; then to attempt, from knowledge of the flow over B, to predict analytically the variations in flow over C and D. The analytical predictions would then be compared with the measured values. Admittedly, this leaves out of consideration the ultimate causative agent, namely, the bubble excitation below stand A. However, it was felt that if the future should show this desireable, it could be studied later. Time and effort were devoted to the development of instrumentation for the purposes noted.

Measurements of the rising and falling water levels in the downstream portions of stands B and C (values y_2 and y_3) were effected by use of Statham pressure transducers having a maximum range of one lb. per sq. in. These instruments are essentially strain wires in a bellows arrangement, and pressure is read as resistance with a Brush strain analyzer working on the Wheatstone bridge principle. The amplified output was applied to a Brush oscillograph, and continuous inked records were obtained. Calibration of the transducers was effected by periodically subjecting them to two known static heads. Figure 8 is a typical example of the records obtained.

Optical methods were employed to obtain records of the fluctuating baffle heads (z_1 and z_2 of figure 4.) In stand B, in particular, the variation was so small that it was hardly discernable to the naked eye. A means of magnification was necessary, and a solution was found in a float driven optical lever system, depicted schematically in figure 9. As the water level rose and fell slightly about the steady-flow level, the float F rose and fell with it. The vertical rod R tilted the lever L in accordance with the float motion and the small mirror M caused the reflection of a light beam to move vertically on scale B. The scale was included in the periodic photography (figure 10.) Magnification factors in the order of 100 were obtained, making it possible to detect water level changes in the order of 0.0001 ft.

The overflow baffles were calibrated as weirs in steady flow, and relationships of the type $Q = Cz^n$ were found empirically. This, of course had to be done with the system in steady flow, and it is worth pointing out that had not the venting proved completely effective in producing steady flow, the calibrations could not have been made. This method worked admirably for recording the quantities z_1 and z_2 since their variations were relatively small. However, it could not be used in stand D for z_3 variations of 8 to 10 inches would occur. A simple, extremely light, float gage was devised for this with no magnification whatsoever, and it was included in the photography. Accuracy was not of high order.

Records of the time variation of z_1, z_2, and z_3 were thus made photographically with a 35 mm. motion picture camera, exposures being made

approximately every 2 seconds. Figure 9 shows one such exposure. Attention is directed to the light spots on the blackboard scales, and to the float gage indicator for z_3 in the lower right hand corner.

The experimental procedure was carried out as follows:

1) A steady flow was established with all vents open.

2) The Brush recording oscillographs were started, calibrated, and synchronized with the clock in the photography.

3) The motion picture camera was started.

4) When the electric clock indicated a prearranged even minute, the vent below stand A was plugged. At that instant unsteady flow was initiated.

Four runs of this type were made. The first turned out to be most complete, and further work was concentrated upon it.

In addition, four runs of a slightly different nature were carried out. Number 7 was selected as having particular interest and is included herein. During the course of the experimentation, it had been observed that vigorous surging would occur whenever a flow change was made, particularly if a sudden change from one steady value was made to a lower steady value. Run No. 7 was of this type. A steady flow of 0.0107 c.f.s. was established. At zero time, this flow was quickly reduced to 0.0070 c.f.s. Violent surges started and gradually died out. No vents were plugged during this run.

The experimental results for runs 1 and 7 are presented in figures 12 to 16 inclusive, plotted for comparison with the theoretical results.

Theory

In the early qualitative stages of this study, the writers felt that they were confronted with an extremely complex phenomenon. So many different things appeared to be happening at once that a quantitative analysis seemed to be impractical. Actually, it turned out to be essentially simple, insofar as the basic notions were concerned.

Referring to figure 4, consider reach 2, consisting of the downstream side of stand B, the upstream side of stand C, and the connecting pipe. Let:

Q_1 = the fluctuating discharge over stand B. This quantity is taken as the given input to the system.

Q_2 = the fluctuating discharge over stand C. This quantity is to be predicted from prior knowledge of Q_1.

V_2 = the velocity in the connecting pipe.

y_2 = elevation of water surface in the downstream portion of stand B, above the baffle crest of stand C.

z_2 = elevation of water surface in the upstream side of stand C, above baffle crest.

Now, the principle of continuity requires that the flow into the downstream side of stand B, less the flow out of it be set equal to the rate at which water is accumulated in it. Expressed as an equation, we have

$$Q_1 - aV_2 = A_2' \frac{dy_2}{dt} \qquad (1)$$

The equation of continuity connecting the pipe line and the upstream side of stand C is, similarly

$$aV_2 - Q_2 = A_2 \frac{dz_2}{dt} \tag{2}$$

The dynamical equation of unsteady flow requires that the total driving head ($y_2 = z_2$) less the friction head be proportional to the acceleration of the fluid column involved. It is

$$y_2 - z_2 - h_{f2} = \frac{1}{g} \frac{dV_2}{dt} \tag{3}$$

Tacit in the above three equations are the following suppositions:

a) Water is completely incompressible. This implies that any pressure changes are transmitted instantly and that the column of water in the pipe line moves as a rigid plug. Expressed mathematically:

$$\frac{\partial V_2}{\partial x} = 0 \text{ for all values of } t.$$

b) The inertia of the water in the stands may be neglected in comparison with that in the pipeline.

c) That the water overpouring in stand B does not add any energy to the system in excess of that expressed by y_2.

The following additional assumptions must be made:

a) that the relationship between discharge and weir head, i.e. between Q_1 and z_1; Q_2 and z_2; Q_3 and z_3 may be expressed as $Q = cz^n$ in which c and n are the same as those observed in steady flow.

b) that the steady-flow values of friction head can be applied to unsteady flow.

In order to effect the solution, each baffle was carefully calibrated as a weir, and the empirical curves relating friction loss to pipe velocity in each reach were obtained.

Using the notations

$$Q_2 = Q\ (z_2) \quad \text{and}$$

$$h_{f2} = h_f\ (V_2)$$

to emphasize these empirical functional relationships, the three equations appear:

$$Q_1 - aV_2 = A_2' \frac{dy_2}{dt} \tag{1}$$

$$aV_2 - Q\ (z_2) = A_2 \frac{dz_2}{dt} \tag{4}$$

$$y_2 - z_2 - h_f\ (V_2) = \frac{l_2}{g} \frac{dV_2}{dt} \tag{5}$$

If now, the third reach is considered, the outflow Q (z_2) of the second reach becomes the inflow to the third. Similar equations may be written for the third reach. They are

$$Q(z_2) - aV_3 = A'_3 \frac{dy_3}{dt} \tag{6}$$

$$aV_3 - Q(z_3) = A_3 \frac{dz_3}{dt} \tag{7}$$

$$y_3 - z_3 - h_f V_3 = \frac{l_3}{g} \frac{dV_3}{dt} \tag{8}$$

This set of six simultaneous differential equations (or, more properly, two sets of three) involve the six unknowns, y_2, z_2, V_2, y_3, z_3, V_3. No direct mathematical methods are available for the solution because the equations are non-linear. The non-linearities partly arise through the empirical functions Q (z) and h_f (V). Moreover, the cross sectional areas of the upstream stands (A'_2 and A'_3) are not constant. This is because during vigorous surging the water level periodically drops below the intersection of the stand and the pipe. Thus, the extreme upstream portion of the pipe functions as part of the stand in providing storage capacity. The A' is therefore a constant for values of y down to the intersection point, then increases very rapidly as the level is lowered further. The relationship between A' and the corresponding y was worked out. A further complication was that the functions Q (z) were zero for values of z equal to or less than zero.

A stepwise numerical method of solution of these equations was first attempted. A run of one minute's duration was analyzed and compared with experimental data (5), requiring about two weeks time to carry out the calculations. The results were sufficiently close to warrant making a long run and doing the calculations on the Differential Analyzer of the College of Engineering, University of California, Los Angeles.

Solution by Differential Analyzer

The mechanical differential analyzer (7, 8) is a computer which solves differential equations by building a model or analogue of these. Quantities are represented on this machine by angular positions of shafts, in revolutions or fractions thereof, from some zero position. The shafts in question are interconnected to the various basic components of the machine which perform the operations of addition and subtraction, multiplication and division, and integration. Addition and subtraction are accomplished by means of differential gears, while multiplication and division are performed by inserting appropriate gear ratios between the shafts on which the variables involved are represented. Integration is done by means of the Kelvin wheel-and-disk integrator (7).

The particular arrangement of adders, multipliers, and integrators is determined by the form of the differential equations to be solved. In the problem at hand, time is the independent variable and is represented by the number of revolutions of a certain shaft. Figure 11 represents the interconnections among the various machine components necessary to solve the first three of the six differential equations. A particularly important feature of the differential analyzer is the ease with which arbitrary functions can be fed into the problem by means of "input tables." For example, in figure 11, input

table 1 is found in the upper left hand corner. This has a graph drawn to some definite scale showing the time variation of the influent quantity Q_1. The revolutions of the time shaft move an indicator horizontally by means of a lead-screw across the table from left to right. A human operator, by means of a crank driving a vertical lead-screw keeps the indicator on the curve. The number of turns made by the operator to do this is proportional to the quantity Q_1. They are delivered, so to speak, to a shaft which carries them to adder 1. Now, the quantity $- aV_2$, which is simultaneously being generated, as will be seen, is also fed to this adder. The output of the adder is the left hand member of equation (1), and when it is multiplied by $\frac{1}{A'_2}$, the output of multiplier 1 is the derivative $\frac{dy_2}{dt}$ (or $\dot{y}_2$ in a more convenient notation). These revolutions go into integrator 1. As this quantity is the integrand, the number of turns representing it operate the lead-screw in positioning the wheel-on-the-disk, while the time shaft is driving the disk. The number of turns of the integrator wheel is the integral $\int \dot{y}_2 \, dt = y_2$, which now is fed back to input table 2. Here, the horizontal axis is driven by the y_2 shaft, while a second operator follows by hand crank the variations in the quantity a/A'_2 which has been plotted out on this table as a function of y_2. The revolutions of the y_2 shaft are also delivered to the vertical lead-screw of output table 1. The time shaft drives the horizontal lead-screw and moves a pen across the table from left to right while the y_2 lead-screw plots the course of the variable y_2 as time proceeds.

Now, y_2 is a variable in equation (5). Its shaft is connected to adder 3 which is also receiving $- z_2$ and $h_f(V_2)$ being generated simultaneously elsewhere in the system. The output of adder 3 is seen to represent the left hand member of equation (5). The number of revolutions representing this quantity are reduced by a constant gear ratio representing $g/1$ in multiplier 3, and turns of this shaft represent the time derivative $\dot{V}_2$ in accordance with equation (5). Integration with respect to time is accomplished as before in integrator 3, and the result is fed back to the horizontal lead-screw of input table 3 where the friction head term is generated by an operator[4] who follows the arbitrary function $h_f(V_2)$ with turns of the vertical lead-screw. These turns are, as has been noted, delivered to adder 3 after going through a 1:1 gear ratio to change the sign. Meanwhile, the revolutions of the V_2 shaft have undergone multiplication by a in multiplier 4, and a sign change, and are fed back into adder 1; thus completing the circuit, so to speak, for equation (1).

At the same time, the shaft revolutions representative of the quantity aV_2 are delivered to adder 2, which is also receiving $- Q_2$, being generated simultaneously. Just as previously described, the left hand member of equation (4) is now the output of adder 2, and subsequent multiplication and integration yields the quantity z_2 in accordance with equation (4). Again, this is fed back to input table 2 as the abscissa while an operator manually generates the turns proportional to $Q(z_2)$, the ordinate. This undergoes a sign change and enters adder 2. The entire circuit is closed by feeding z back also into adder 3. All of the output tables are driven horizontally by the time shaft, and the results, namely y_2, z_2, V_2, and $Q(z_2)$ are automatically plotted on them.

4. Actually, an automatic "curve follower" was used on this table, which eliminated the need for an operator.

The second three equations are solved by similar interconnections among the elements of the differential analyzer. All subscripts are increased by one, meaning that the outflow Q_2 of the second reach becomes the inflow to the third.

It is to be noted particularly that the analyzer connections form a completely closed loop. This means that, although the description may have indicated that events such as multiplication, integration, etc. are taking place consecutively, actually these operations take place simultaneously.

Results

As regards run no. 1, figure 12 shows the values of Q_1, Q_2, and Q_3 for the entire eleven minutes of run. Q_1 is shown as observed, and as used on table 1 for the input to the differential analyzer. Q_2 is given as observed on the model and as calculated by the differential analyzer, and Q_3 is given as calculated. The values observed for z_3 were not believed to be of sufficient accuracy to warrant computation of Q_3 therefrom.

Unfortunately, the optical system for measurement of z_1 was so adjusted during run no. 1 that the knife edge of the lever L apparently hit the side of the groove in which the knife pivoted. This affected readings around and above 0.010 c.f.s., and the arbitrary dotted line correction shown was made.

The scales on which the various observed and calculated values were plotted were found to vary slightly. This was only 4 to 5 seconds in the total 11 minutes, but enough to make the observed and calculated surges appear somewhat out of phase with each other. Rather than to replot the data, the simple expedient was used in preparing the charts of matching the curves at zero time on figure 12A, and at the end of run (11 minutes) on figure 12B. Towards the right on 12A, and towards the left on 12B, the curves therefore appear slightly off phase.

In the middle of the run there is a break in the experimental Q_2 curve. At that time a violent surge happened to throw the rod R off from the lever L of the optical system for measuring z_2. A few seconds elapsed before it could be put back in order.

Some of the other data, both observed and calculated, of run no. 1 are shown in figure 13. These include values of y_2, z_2, y_3, z_3, and V_3. It was believed adequate to plot only the first two and the last two minutes of the run for these data.

The values of Q for run no. 7 are shown on figure 14. In this run, at zero time, Q_0 was dropped from 0.0107 c.f.s. to 0.0070 c.f.s. Such a change invariably produces violent surging which gradually dies out. All vents in the model were open. The change in Q occurred above reach 1; therefore the first stage of amplification is reach 1 instead of reach 2 as in run no. 1.

It was noted that the observed and calculated data were somewhat out of phase for run 7. To see if this was caused by the time it actually took on the model to change the flow (change was presumed to be instantaneous on the differential analyzer) another solution (solution no. 3) was attempted on the differential analyzer. In this solution, figure 15, Q_1 observed was put on to the input table instead of Q_0. This indicated that the differences in phase were caused by the time it actually took to change the flow on the model. Q_3 and z_3, obtained for run no. 7, solution no. 3, are also shown.

For run no. 1 the observed surges were noted to be of somewhat greater amplitude than the calculated surges, particularly for reach 3. This tendency was even more apparent in run no. 7, and, in addition, observed surging

was more sustained than was calculated. Lesser friction loss in the pipe lines than determined for steady flow was a possible explanation of this. Values of friction loss for reach 2 pipe line as set up on the differential analyzer, were therefore reduced 1/4 (solution no. 4) and 1/2 (solution no. 5). The Q_2 surges, figure 16, calculated under these conditions were greater, but not more sustained. It was therefore concluded that values assigned to pipe friction loss were not the cause of differences in observed and calculated surges.

It is altogether probable that some differences in observed and calculated values can be explained by inertia of and/or by the inaccuracy of the system of instrumentation. Upon careful review of the data, however, it has been concluded that differences that could be so explained were relatively minor.

There remain two of the original suppositions pertaining to the theory that may contribute to the differences, namely:

a) Neglect of the inertia of the water in the stands.

b) Neglect of the energy periodically fed into a reach by the falling water from the preceeding reach.

In addition to these effects, there was also present the fact that a certain fraction of the air entrained by the overfalling nappe bubbled directly back through the stand without ever having reached the pipe. This was a continuous process and therefore a part of the storage volume was taken up by air under the water surface. This had the net effect of decreasing the cross sectional area A' of the stand. Had a correction been made for this, a smaller numerical value for the factor A' would have been used in the analyzer solution, with the result that the calculated amplitudes would have been larger. Since it was not known how to make such a correction, it is reasonable that the observed amplitudes be slightly larger than those calculated. In this regard, it will be recalled that the ability of free falling water to entrain air does not scale down. Hence, in constructing the model it was necessary to provide higher stands than strict model proportion would have provided. Thus, any inaccuracy in the theory caused by the above named suppositions would be of considerably less importance in a normal prototype than in this model.

Conclusions

1. In the model experiments surge was initiated below an overflow stand by the entrainment of air in the downpouring water, by the collection of that air in a bubble immediately downstream from the stand, and by the periodic blowing back of that bubble into the stand.

2. This surge initiation can be completely eliminated by vents of large size placed immediately downstream from the stand.

3. Surge, initiated in an open type pipe system, is amplified in subsequent reaches downstream, provided the natural frequencies of succeeding reaches are close enough to the frequency occuring in the original reach. Fluctuations not in phase may cause amplification, but the surging will tend to die out, and surges not in phase will tend to be filtered out.

4. Venting, as provided to prevent surge initiation, will have no significant effect upon amplification of surge.

5. The theory presented provides a substantially accurate quantitative evaluation of surge amplification. Any tendency for observed amplification to exceed calculated amplification can be explained apparently by the suppositions required for simplification of the theory. In proto-types, any differences between observed and calculated surge should not be of appreciable magnitude.

6. Considerable work can be done to set up criteria by which surge difficulties in open type systems can be minimized. However, such techniques generally amplify problems of regulating open type systems. Therefore, the writers recommend that systems which contain inherent oscillatory properties, as does the open type system, be no longer built.

Note

The writers have known for two years, because of the report by Curtis (1), that the U. S. Bureau of Reclamation has been conducting some model experiments on the phenomenon of surge in open systems, and the Bureau was advised of our progress [Reference (4) forwarded on December 17, 1952.] We were not aware, however, that they had in some respects obtained findings parallel to ours until we received, on June 16, 1953, a copy of a paper presented before the annual meeting of the Western Concrete Pipe Association on March 27, 1953 by E. C. Fortier, Engineer, U. S. Bureau of Reclamation. This paper made reference to U. S. B. R. Hydraulic Laboratory Report No. Hyd-324. Upon request, we obtained a copy of report no. Hyd-324, "Hydraulic and Analytical Studies of the Causes and Control of Surging in the Coachella Irrigation Distribution System—All American Canal System—Boulder Canyon Project", on July 10, 1953 from L. N. McClellan, Chief Engineer, U. S. B. R. This was after we had completed all experimental and analytical work, and had prepared the first draft of this paper. Upon request of Mr. McClellan, we have neither referred to their report, nor made use of any data or findings contained therein. We suggest, however, that anyone interested read their report since in some respects the two endeavors are parallel, and in others they are complementary.

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FIGURES

1. Schematic profile of an open type pipe lateral.
2. Schematic diagram of the model.
3. Photograph of the model stands (instrumentation incomplete).
4. Notations used with the model studies.
5. Profile of an overflow stand showing bubble formation.
6. Photograph of bubble forming below a stand.
7. Photograph of a vented overflow stand on the model.
8. Sample of records obtained on the oscillograph of fluctuations in y_2 and y_3.
9. Schematic diagram of the float driven optical lever system for determination of z_1 and z_2.
10. One frame from the motion picture made to record the fluctuations of z_1, z_2, and z_3 with time.
11. Interconnections among the various differential analyzer components necessary to solve the first three of six differential equations of the surge problem.
12. (A and B) Records of discharge from the various reaches plotted against time in minutes. Q_1, from experimental observation, was fed into the differential analyzer, producing Q_2 (calculated) and Q_3 (calculated). For comparison Q_2 (observed on model) is plotted with Q_2 (calculated). Run no. 1, Q_O = 0.00683 c.f.s. In matching the observed and computed data, it was noted that a slight error in the scale on which Q_1 was plotted and fed into the differential analyzer (a total overlength of 4 seconds in 11 minutes) existed. Q_2 and Q_3, as calculated on the machine, had a total overlength of 5 seconds. To avoid tedious replotting, the data were simply matched at zero time in figure 12A, and plotted forward; and were matched at 11 minutes (end of run) on figure 12B, and plotted backwards. Slight discrepancies therefore exist towards the right on A, and towards the left on B.
13. Records of y_2, z_2, y_3, z_3, and V_3, as observed on the model, and as calculated on the differential analyzer. Run no. 1, Q_O = 0.00683 c.f.s. First two, and last two minutes only shown. Records for first two minutes matched at zero time; records for last two minutes matched at end of run (11 minutes).
14. Discharge over baffles at stands B, C, and D (Q_1, Q_2 and Q_3) plotted against time for run no. 7, solution no. 2. At zero time Q_O was dropped from 0.0107 c.f.s. steady flow to 0.0070 c.f.s. steady flow upstream from stand A. The change was instantaneous on the differential analyzer, but took a finite time—possibly two seconds or so—on the model. Vents below all stands were open. The first stage of amplification was therefore in reach no. 1, with two more stages following in reaches 2 and 3. Values of Q_1, Q_2, and Q_3 as calculated by the differential analyzer are shown; and values of Q_1 and Q_2 as observed by instrumentation of the model are shown.

15. Results of solution 3, run no. 7. Solution of same run as shown on figure 14 except that Q_i calculated used as the input to the differential analyzer instead of Q_O observed. Principal result of this solution was to show that the time required to change the flow at the beginning of run 7 was responsible for throwing the observations on that run slightly off phase, but did not affect the magnitude of the surges.

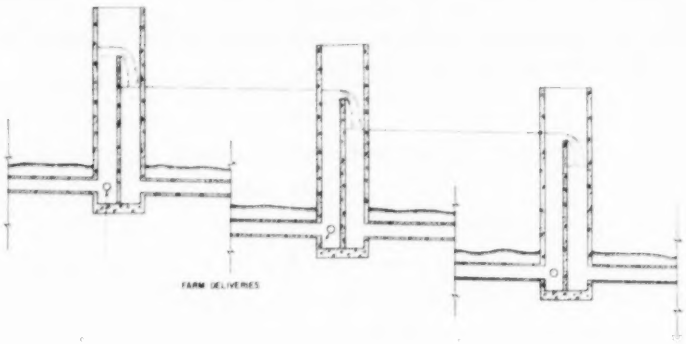
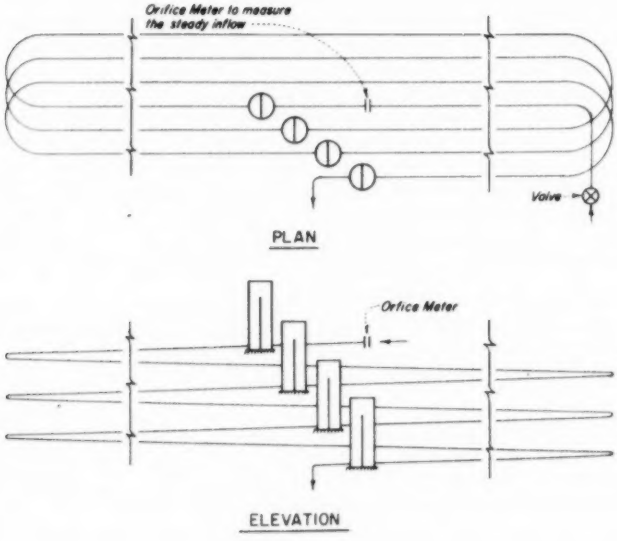


Figure 1



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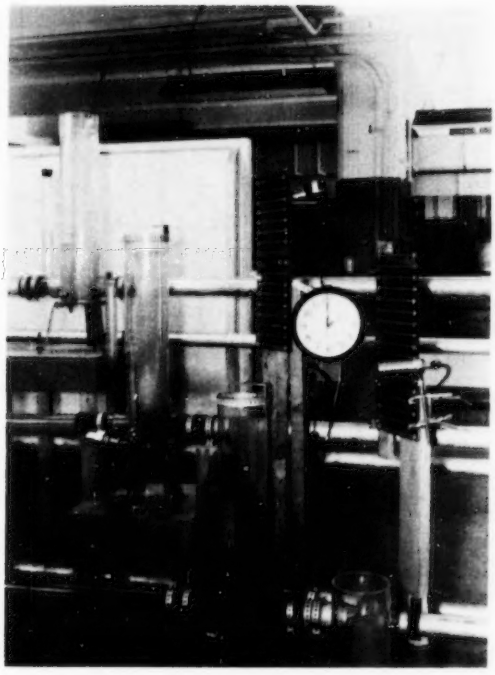


Figure 3

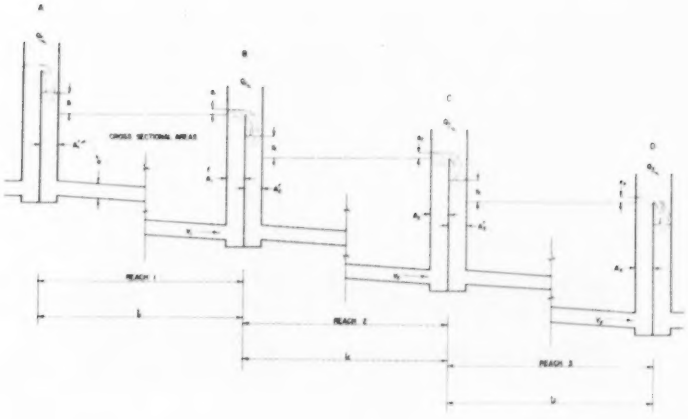


Figure 4

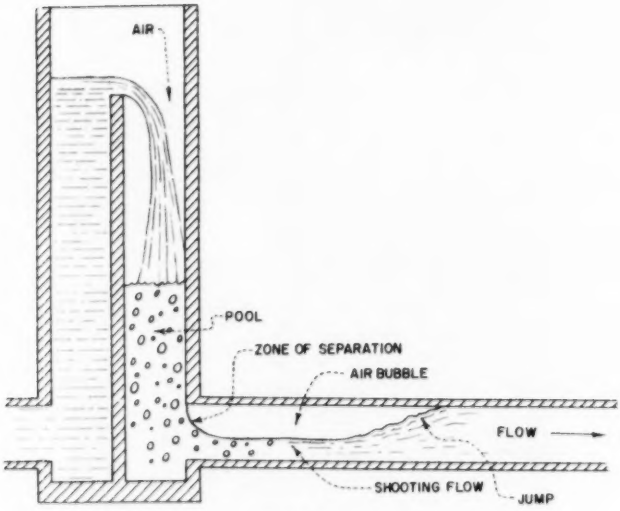


FIGURE 5

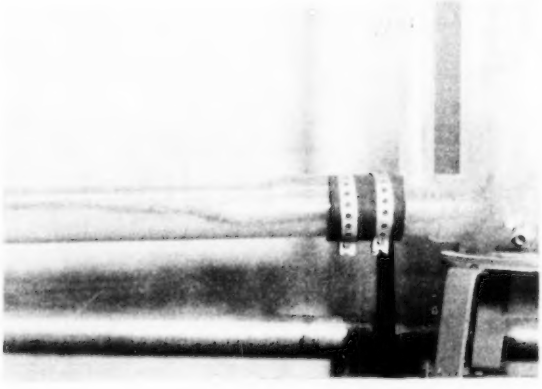


Figure 6

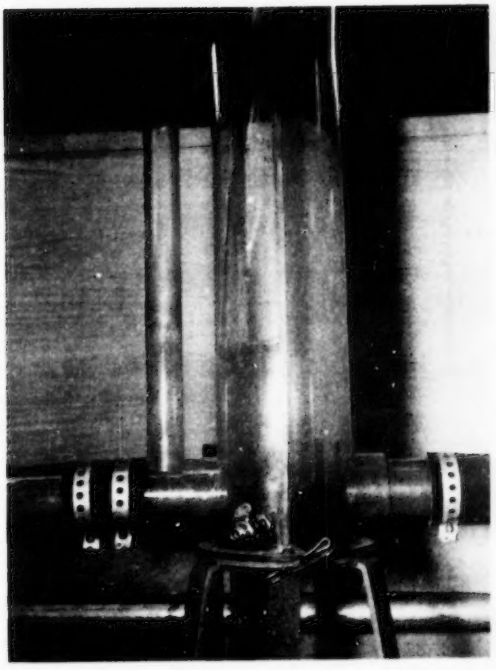


Figure 7

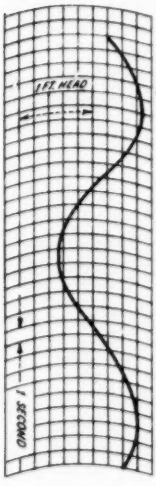


Figure 8

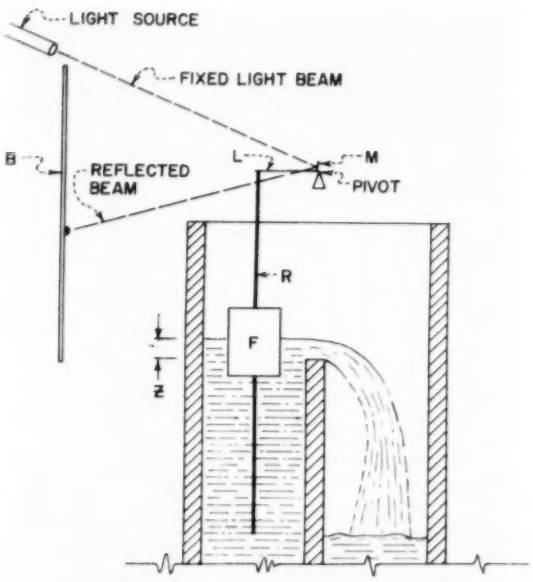


FIGURE 9

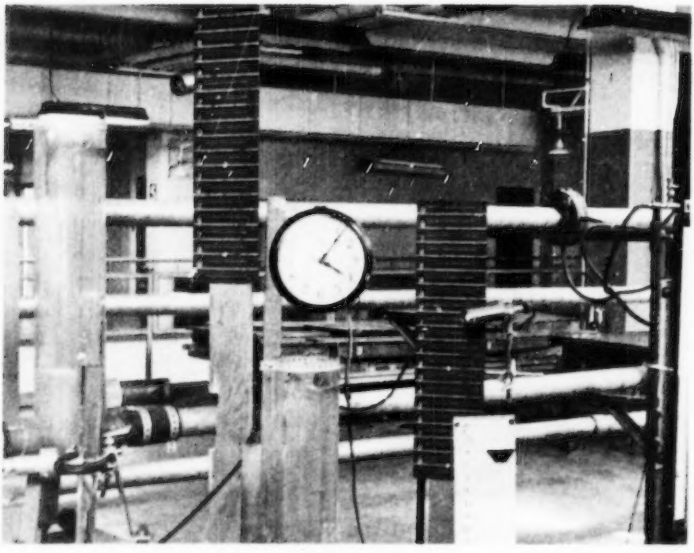


Figure 10

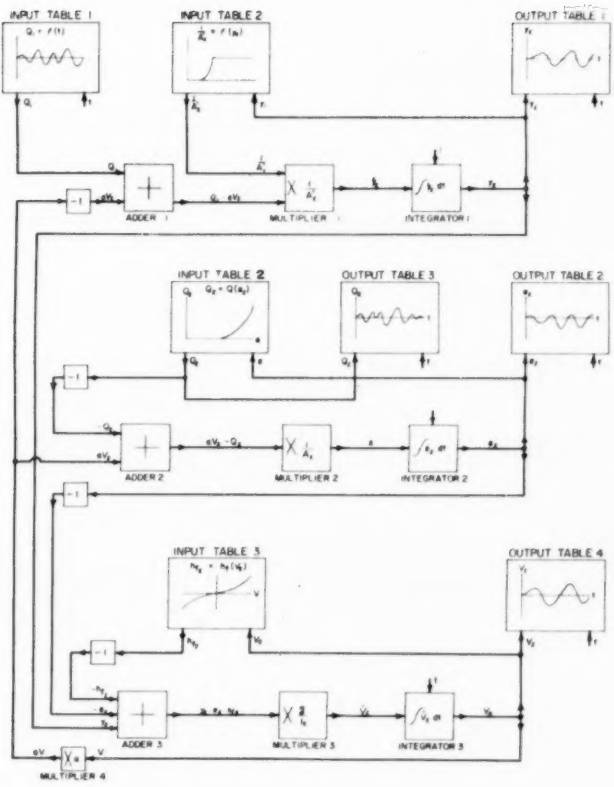

INPUT TABLE 1
INPUT TABLE 2
OUTPUT TABLE 1
ADDER 1
MULTIPLIER 1
INTEGRATOR 1
INPUT TABLE 2
OUTPUT TABLE 3
OUTPUT TABLE 2
ADDER 2
MULTIPLIER 2
INTEGRATOR 2
INPUT TABLE 3
OUTPUT TABLE 4
ADDER 3
MULTIPLIER 3
INTEGRATOR 3
MULTIPLIER 4

Figure 11

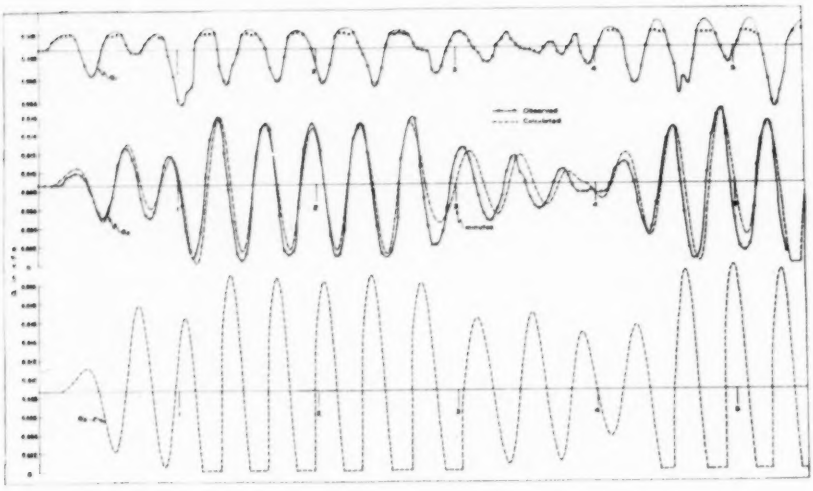


Figure 12a

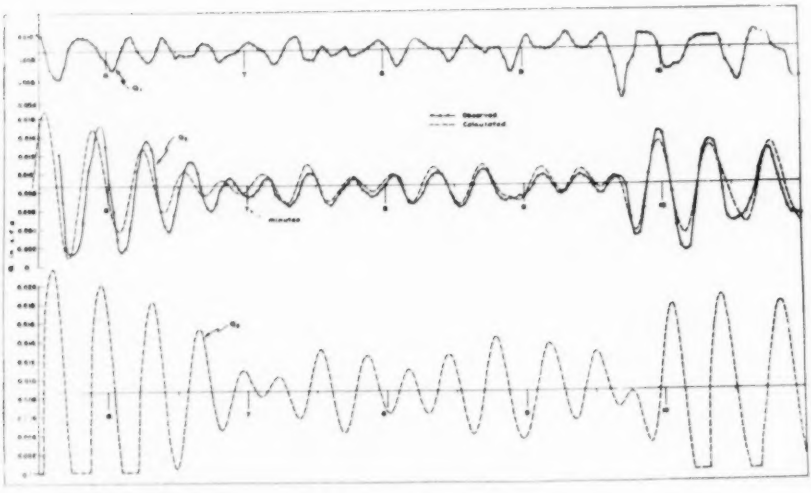


Figure 12b

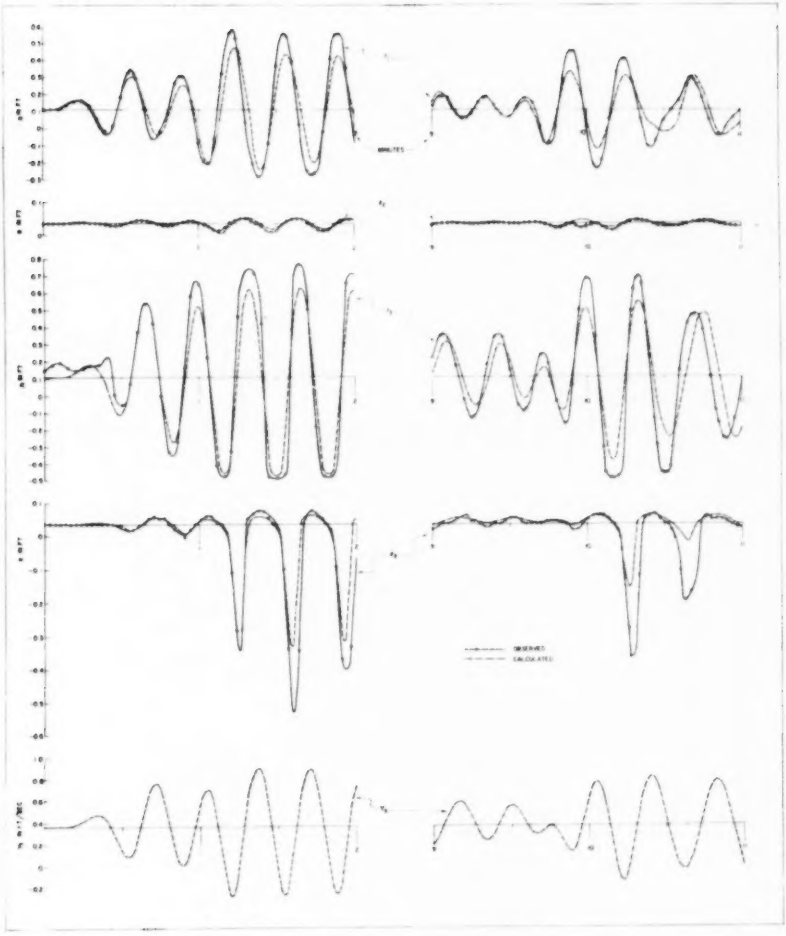


Figure 13

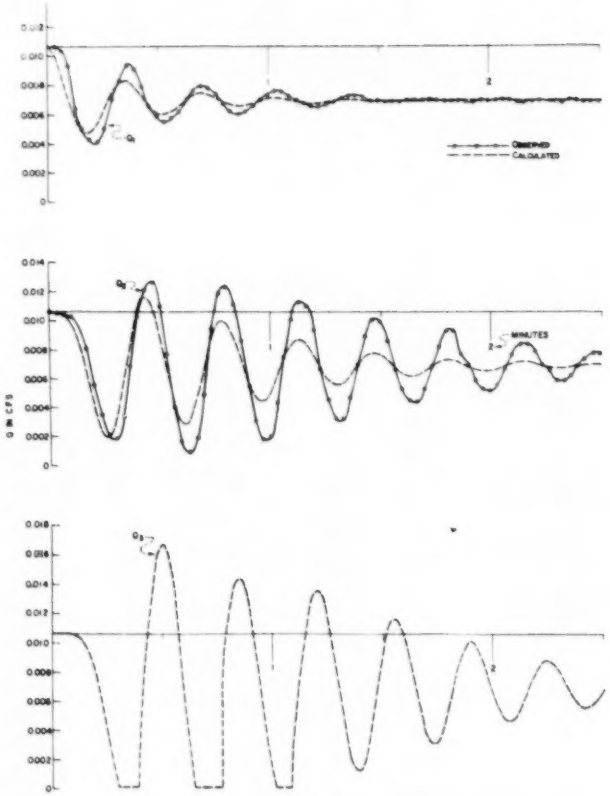


Figure 14

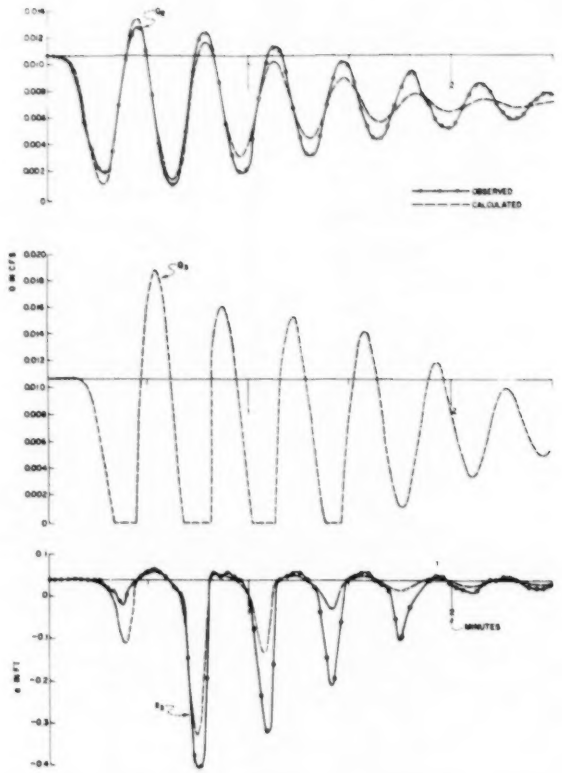
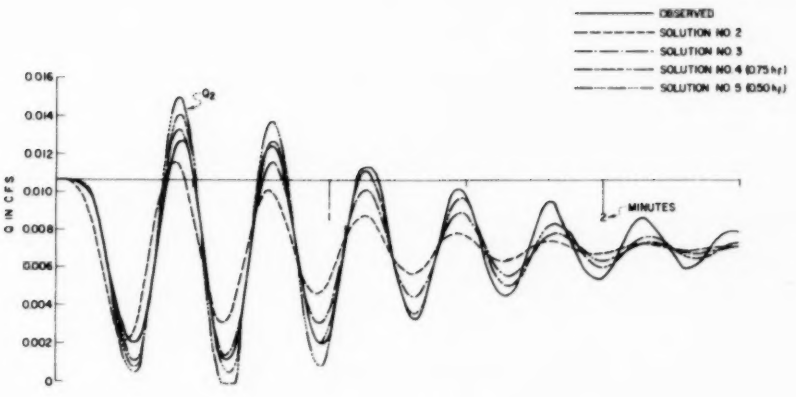


Figure 15


OBSERVED
SOLUTION NO. 2
SOLUTION NO. 3
SOLUTION NO. 4 (0.75 hr)
SOLUTION NO. 5 (0.50 hr)
Q IN CFS
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0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
Q_2
2
MINUTES

Figure 16

PROCEEDINGS-SEPARATES

VOLUME 79 (1953)

The technical papers published in the current calendar year are presented below. Technical division sponsorship is indicated by an abbreviation at the end of each Separate Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways (WW) divisions. For titles and order coupons, refer to the appropriate issue of "Civil Engineering."

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JULY:[a] 200(SM),[b] 201(ST),[b] 202(EM),[b] 203(SA),[b] 204(AT),[b] 205(EM),[b] 206(ST),[b] 207(SA),[b] 208(SA),[b] 209(ST),[b] 210(SU),[b] 211(EM),[b] 212(SU),[b] 213(IR),[b] 214(HW),[b] 215(SM),[b] 216(ST),[b] 217(ST),[b] 218(ST),[b] 219(ST),[b] 220(SM),[b] 221(HW),[b] 222(SM),[b] 223(EM),[b] 224(EM),[b] 225(EM),[b] 226(CO),[b] 227(SM),[b] 228(SM),[b] 229(IR).[b]

AUGUST: 230(HY), 231(SA), 232(SA), 233(AT), 234(HW), 235(HW), 236(HW), 237(AT), 238(WW), 239(SA), 240(IR), 241(AT), 242(IR), 243(ST), 244(ST), 245(ST), 246(ST), 247(SA), 248(SA), 249(ST), 250(EM),[c] 251(ST), 252(SA), 253(AT), 254(HY), 255(AT), 256(ST), 257(SA), 258(EM), 259(WW).

SEPTEMBER: 260(AT), 261(EM), 262(SM), 263(ST), 264(WW), 265(ST), 266(ST), 267(SA), 268(CO), 269(CO), 270(CO), 271(SU), 272(SA), 273(PO), 274(HY), 275(WW), 276(HW), 277(SU), 278(SU), 279(SA), 280(IR), 281(EM), 282(SU), 283(SA), 284(SU), 285(CP), 286(EM), 287(EM), 288(SA), 289(CO).

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a. Beginning with "Proceedings-Separate No. 200," published in July, 1953, the papers were printed by the photo-offset method.

b. Presented at the Miami Beach (Fla.) Convention of the Society in June, 1953.

c. Presented at the New York (N.Y.) Convention of the Society in October, 1953.

d. Beginning with "Proceedings-Separate No. 290," published in October, 1953, an automatic distribution of papers was inaugurated, as outlined in "Civil Engineering," June, 1953, page 66.

e. Discussions, grouped by divisions.

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